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Limited area broadcast for warning message delivery over vehicular ad-hoc networks

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Abstract

Vehicular ad hoc networks have been developed in consideration of advancing driving safety. In driving-safety applications, rapid dissemination of warning messages is highly demanded to avoid accidents involving incoming vehicles. Broadcast transmission is considered the most appropriate technique to spread warning messages because it can simultaneously reach all neighboring nodes within a transmission range using only a brief wireless media access. However, blindly broadcasting redundant messages may severely overcrowd wireless media channels and provoke transmission collisions; this is known as the broadcast storm problem. In order to reduce broadcast redundancy, broadcasting must be intelligently controlled. Simultaneously, an intelligent broadcast scheme should aim to reduce the number of hops needed to arrive at a destination, to achieve smaller propagation delay. In this paper, we observed the behavior of a few broadcast schemes and found that their performances can be explained as limiting a space to control the number of contentions in broadcasting. From the observation, we propose a limited area-based (LAB) scheme to achieve a shorter propagation time as well as a smaller number of redundant broadcast messages. The proposed scheme can maintain a proper collision rate to obtain a faster propagation time by adjusting the size of an area in which broadcasting nodes belong. Performance evaluation results from simulation show that the proposed scheme is feasible and reasonable.

Keywords: Vehicular ad hoc networks, Broadcast storm, Warning message dissemination, Limited area broadcast

1 Introduction

Vehicular ad hoc networks (VANETs) are developed as a component of intelligent transportation systems (ITS) technology to increase driving safety [1]. In driving-safety applications, rapid dissemination of warning messages is highly demanded to avoid accidents involving multiple incoming vehicles [2]. In order to achieve rapid message dissemination, broadcast transmission is considered the most appropriate technique to spread warning messages because it can simultaneously reach all neighboring nodes within a transmission range, using only a brief wireless media access [3]. Thus, driving-safety applications of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications are implemented using wireless communication techniques such as dedicated short-range communications (DSRC) and IEEE 802.11p [1]. Moreover, the broadcasting process is significantly important in various routing protocols, for building backbone topologies or node connectivity in mobile ad hoc networks (MANETs) [4–7].

However, broadcast transmission can introduce weaknesses such as unreliable transmission, uncontrolled congestion, and hidden terminal problems. [8]. Redundant broadcast messages from a blind broadcast of a warning message may severely overcrowd the wireless media channel, causing a significant amount of transmission collisions; this is known as the broadcast storm problem [1, 9, 10].

Moreover, the broadcast storm problem will worsen as a network's density increases. In a pileup scenario, such as the example depicted in Fig. 1a, the broadcast of a warning message will cause the message to be distributed to all cars inside the transmission radius and propagated to the next hops after the incident.

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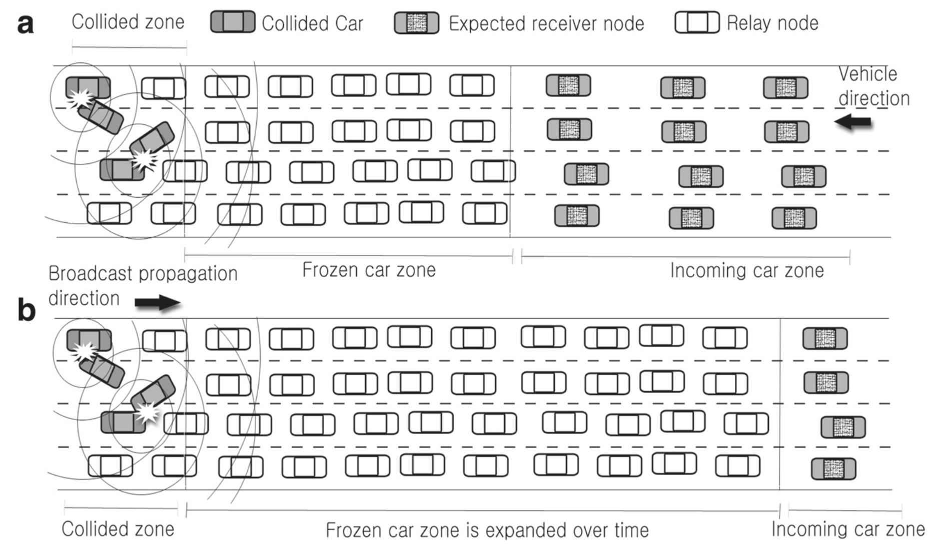

Fig. 1 Four-lane traffic accident scenario. **a** Three sections on the road: collision area, frozen area, and incoming cars area. **b** The denser collision area

The number of incoming cars will increase in the time after the accident, as depicted in Fig. 1b. Thus, the problem caused by the blind broadcast becomes worse because the number of cars trying to generate the redundant warning messages increases as the number of cars in a transmission radius increases over time.

In order to reduce the redundant broadcast messages and mitigate the broadcast storm, the broadcast itself needs to be intelligently controlled. In other words, not all nodes should be allowed to rebroadcast the message—only a good selected relay node should be permitted to do so. Thus, designing an intelligent broadcast scheme will involve designing criteria to choose a good relay.

Most of the intelligent broadcast schemes introduced in this paper's literature [11–20] are designed to select a good relay to reduce of redundant broadcast messages. Priority-based, probabilistic-based, counter-based, and other broadcast schemes [14–20] focus on efficiently suppressing broadcast message redundancy to reduce collision rates. To reduce the redundant messages, distance-based broadcast schemes [11–13] select the furthest node as a relay node to minimize the number of hops and to decrease collision rates by controlling the size of the contention window based on distance.

In Section 3, we observed the behavior of a few broadcast schemes and found that they limited transmission space to control the number of contentions in broadcasting. Thus, in order to achieve better performance in disseminating warning messages, or to shorten the propagation delay, a proper space limitation should be performed to efficiently lower the collision rate as much as possible, to realize a faster propagation time. However, most of the previous schemes only consider controlling their contention windows without the concept of space limiting; as a result, they are losing an opportunity to achieve smaller propagation delay.

Based on this motivation, we propose a limited area broadcast (LAB) scheme to achieve a shorter propagation time and reduce the number of redundant broadcast messages.

To meet this goal, this scheme is designed to achieve a proper relation by adjusting or limiting the size of the area in which broadcasting nodes belong; this implies that only the nodes belonging to the area can rebroadcast. In this manner, our scheme can maintain a proper collision rate to obtain a faster propagation time. Performance evaluation results from an extensive simulation show that our claim is reasonable. Thus, the contributions of this paper can be summarized as follows.

- Identifying the performance bottlenecks of broadcast schemes with contention window distributions on geographical space
- Proposing a new broadcast scheme, called a space-limited broadcast, based on the observation
- Evaluating the effect of space limiting through extensive simulations

The remaining sections are organized as follows. Section 2 describes related works pertaining to the broadcasting of warning messages. Section 3 explains the observation details of conventional broadcast schemes. Section 4 provides the description of the LAB scheme. Section 5 discusses the simulation results in terms of metrics such as propagation time, and collision rate. The conclusions will be given in the last section of this paper.

2 Related works

Many researchers have proposed various broadcast schemes to mitigate the broadcast storm problem. Depending on the method used to choose a broadcast relay, each scheme can be classified into categories such as probabilistic-based broadcast, counter-based broadcast, density-based broadcast, and distance-based broadcast. To learn about other interesting issues related to broadcast forwarding and routing, readers can refer to [21–26].

2.1 Priority-based broadcast

In a priority-based scheme, a message is categorized into one of multiple classes depending on the degree of importance or priority. According to the assigned priorities, the messages are differently scheduled so that more important or higher priority messages are transmitted first rather than less important or lower priority messages [14–18]. Along with this context, a warning message is classified as the highest priority message, to be transmitted earlier than any other messages.

In a traffic accident situation, however, the population of the nodes broadcasting the warning message increases rapidly, and network traffic will be dominated by the warning messages, all with the same high priority. Thus, every node in the transmission range may compete to transmit the same priority message which causes the broadcast storm problem again.

2.2 Probabilistic-based broadcast

The purpose of this scheme is to reduce the amount of network traffic transmitted from the network layer to the data link layer by assigning a probability to a node whenever it has a packet to transmit [9, 20]. Depending on how the assigned probability is utilized, p-persistence, slotted 1-persistence, and weighted p-persistence broadcasting are proposed.

In p-persistence broadcasting, as the simplest form, when a node has a packet to transmit, it determines a probability number between 0 and 1. If the selected number falls into a predefined range or threshold, i.e., between 0 and 0.5, the packet would be immediately transmitted. Otherwise, the packet would be dropped. Thus, the amount of broadcast traffic will be reduced by half, and the broadcast problem will be reduced.

The notion of time division multiple access (TDMA) is incorporated in slotted 1-persistence. A time line is divided into a series of time slots, and a node is assigned to one of them. When a node has a packet to transmit, the node can transmit the packet only during the assigned time slot with the probability of 1. During other time slots not owned by the node, the node must wait for its time slot. Through this process, the degree of competition in packet transmission would be lower.

Weighted p-persistence combines the previous two methods. A transmission probability of 1 in slotted 1-persistence is adjusted into a probability of p. Thus, during the assigned time slot, the node should determine its probability number. Transmission of the packet is allowed only if the selected probability number belongs to the threshold. Otherwise, the packet transmission would be cancelled.

In summary, probabilistic-based broadcast schemes randomly choose a few relay nodes and do not allow all nodes to broadcast, in order to suppress redundant broadcast messages. However, the random selection is not efficient enough to achieve our goals because we cannot easily determine a proper threshold that would be sensitively affected by a network's density. The survey of probabilistic broadcast schemes is explained in detail by [27].

2.3 Counter-based broadcast

As the name counter-based scheme implies, a counter value or a threshold is introduced to count the number of identical broadcast messages that are overheard, in order to alleviate the broadcast storm [19]. Whenever a node receives a broadcast message for the first time, the node postpones the transmission for a while (during a so-called back-off time) before the actual transmission in order to avoid a transmission collision because it follows carrier sense multiple access and collision avoidance (CSMA/CA).

Overhead packet are counted during this back-off time. The node would inhibit the transmission if the counted number reaches a predefined number; when this occurs, this implies that numerous neighboring nodes have already rebroadcasted the message. Thus, the node abandons its transmission to avoid broadcasting the redundant message again.

This scheme appears similar to the probabilistic-based scheme in that it tries to adjust the amount of traffic flooding over a network by limiting broadcast transmissions whenever the counter reaches a certain threshold.

2.4 Density-based broadcast

In probabilistic-based broadcast, the probability number used to determine whether to forward a message is fixed regardless of how many nodes exist in a network. This fixed probability may cause a problem in which collisions would increase if a part of the network is densely populated. Otherwise, if a part of the network is relatively sparse, all of the nodes in the area happen to drop the broadcast.

To address this problem, density-based schemes were introduced to allow the probability to reflect the density of network and be properly adjusted according to the density [28, 29].

In a density-based scheme, each node usually counts the number of neighboring nodes by overhearing hello messages or flying peer-to-peer messages. When a node receives a broadcast message, it determines its sending or discarding with its own probability $\frac{k}{n}$, where k is a given parameter and n is the number of counted neighboring nodes or the degree of the density. The probability will be increased or decreased depending on n to mitigate the aforementioned problem. However, in VANETs, the network densities vary over time; thus, correctly counting n is the most important issue of the density-based scheme.

2.5 Distance-based broadcast

In previous probabilistic broadcast schemes, the rebroadcasting nodes were randomly selected irrespective of the distances between the sender and the receivers. These selections may tend to increase the number of transmission hops to a destination. To minimize the number of hops, and achieve an expected decrease in propagation delay, [11–13] developed distance-based broadcast schemes considered the distance between senders and receivers. They assign higher rebroadcasting privileges to nodes located close to the border of the transmission range. The differentiated privileges are determined using inverse proportional mapping from the measured distance to the size of the contention windows (CWs) of the receivers.

Depending on how the distance is measured, distance-based broadcast schemes can be divided into one of two methods: geographic distance (GD)-based broadcast and received-signal-strength (RSS)-based broadcast. A GD-based broadcast scheme calculates the distance between the sender and receiver using location information provided by the global positioning system (GPS). An RSS-based broadcast scheme estimates the distance based on the power of the signal received by the receiver [20].

Thus, one of the further nodes from a sender is more likely to forward the broadcast message, while other nodes ready to broadcast the same message will cancel their rebroadcasting immediately after the first rebroadcast. The scheme is known to be effective in suppressing redundant broadcasting and in reducing the total number of hops to a destination.

3 Observation of four broadcast schemes

In this section, we investigate warning messages dissemination techniques by comparing two distance-based broadcast schemes and two simple broadcast schemes; the comparison measures propagation delays and collision rates through extensive simulations.

3.1 Comparison environment

The two distance-based broadcast schemes consist of a GD-based broadcast scheme and an RSS-based broadcast scheme. The two schemes use different techniques to estimate the distance between a broadcast sender and a receiver.

Algorithm 1 Broadcast procedure of simple broadcast scheme

```
function RECEIVEBCASTMSG()
    msgID → stored                          ▷ store the message ID
    if packet(msgID) > 1 then               ▷ receive more than 1 packet
        drop packet;
    end if
    BCASTMSG(r);                            ▷ call this function
end function
function BCASTMSG()
    CW = CWmin    ▷ set CW size as minimum CW, and set maximum CW for SB-1024
    rslot = random(CW);                     ▷ set the slot
    if rslot = 0 then                       ▷ Count down the slot
        SENDBCAST();                        ▷ Call this procedure
        packet(msgID) → sent                ▷ reset the backoff timer
    end if
end function
```

For the simulation comparison baseline, we have considered two simple broadcast schemes with fixed maximum contention window (CWmax) values of 64 and 1024, respectively. The fixed contention window (CW) was introduced in order to understand the CW's effect on propagation delay and collision rate in broadcasting.

Note that the simple broadcast scheme used in the comparison is similar to the pure broadcast scheme.[1] However, it is modified to forward a broadcast message only once, when a node overhears the message for the first time. If the node overhears the same message again, it ignores the message and does not forward it. The detailed procedure of the simple broadcast scheme is described in Algorithm 1.

The simulation was performed using the same scenario and parameters described in Section 5. After the simulation, we plotted Fig. 2 to represent the relation between the propagation delays and collision rates of four broadcast schemes. A single point in the figure represents a pair of an averaged propagation delay (x-axis) and the averaged corresponding collision rate (y-axis).

In Section 3, a propagation delay is defined as the start of a broadcast from a car accident scene to the arrival at the destination behind the frozen area. The number of collisions is the number of counted collisions during the single propagation delay.

For each broadcast scheme, we plotted 12 points, which are divided into three four-point groups. The three groups correspond to three types of network densities: low (25

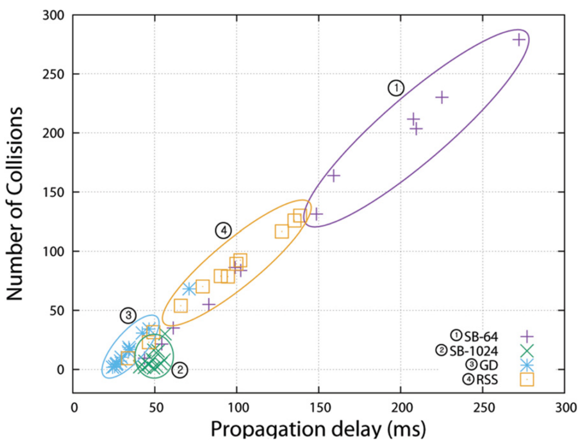

Fig. 2 Distribution of propagation delay and collisions of three broadcasts measured in low, medium, and high densities with different broadcast senders

cars/km/lane), medium (50 cars/km/lane), and high (100 cars/km/lane). A single point in one group (or a single network density) corresponds to the number of initial broadcast senders, i.e., 1, 2, 3, or 4. For example, the number 4 emulates a scenario in which four cars crash and begin broadcasting at approximately the same time. In order to obtain a single point, 1000 simulation runs were repeated with different random seeds, and the results were averaged to achieve a 95 % confidence interval [30].

To simplify Fig. 2, we did not include marks to differentiate the types of network densities or the number of the broadcast senders because we observed the same behaviors for all four broadcast schemes in all network densities: a lower number takes a lower collision rate. For example, in any group, the number 1 always achieved the lowest collision rate and the number 2 took the second lowest collision rate, and so on. Finally, the highest collision rate was given by the number 4.

3.2 Observations

The first observation from Fig. 2 is that SB-1024 is comparable to GD even though SB-1024 is slightly slower than GD, in propagation delay with similar collision rates. Moreover, RSS is worse than SB-1024, which was unexpected. We expected the distance-based schemes to be better than the simple broadcasts because the distance-based schemes efficiently determine CW sizes in situation where more senders in a higher network density cause more collisions. SB-64 reflects this expectation well. However, SB-1024 shows stable behavior irrespective of the number of senders and the network densities. We attempted to determine the reason for the phenomenon depicted in Fig. 3.

Figure 3 describes the CW distributions of each broadcast scheme. The CW distributions of SB-64 or SB-1024 can be represented with a single circular area as depicted in Fig. 3b because CWs are randomly determined between 0 and 63 or 1023. The sizes of CWs are not sorted and geographically ordered. Each broadcast node in SB-1024 will have enough slots in its CW selection between 0 and 1023, which results in a few collisions before a successful broadcast. Contrary to SB-1024, because SB-64 does not have enough slots, the number of collisions and the propagation delay are sensitively affected by the number of senders or the network density.

Compared to SB-64 and SB-1024, we can represent the CW distribution of GD with evenly spaced circular areas or shells as depicted in Fig. 3a because the CWs of GD are linearly determined by the geographical distance between a sender and the receivers.[2] Thus, the sizes of CWs in each area will be sorted and ordered with $CW^1 < CW^2 < ... < CW^n$.[3] The CW^1s in the outmost circular area will be smallest and equal to CWmin(= 32) while the CWs in the inner circular regions will be larger than CW^1.

GD's actual competitions for broadcasting primarily occur in the outmost circular area. As the network density increases, the number of nodes in the outmost area increases, which also leads to more frequent collisions. We can see this behavior in the graph, where the number of collisions is almost zero. When the collisions are almost zero, the propagation delay of GD is much faster than that of SB-1024, which means most broadcasts occur in the outmost area. When the number of senders or the network density increases, the increases in propagation delay and the number of GD collisions means that successful broadcasts occur more often in inner areas, owing to the collisions in the outmost area.

The second observation from Fig. 2 is that RSS unexpectedly shows higher collision rates with longer propagation delays, unlike GD. This poor performance is due to the difference in the two schemes' distance measurements.

In the radio propagation models, the signal strength is inversely proportional to the square of the distance between a sender and a receiver [31], whereby the CWs of RSS are inverse-exponentially determined. Thus, we can represent the CW distribution of RSS with non-evenly spaced circular areas or shells, as depicted in Fig. 3c. Even though the CWs are sorted and ordered with $CW^1 < CW^2 < ... < CW^n$, the outmost circular area is much thicker than the others. Because the outmost area of RSS is much larger than that of GD, the number of the actual competitions for broadcasting in RSS seems to be too high to avoid collisions, which results in a propagation delay that is longer than that of GD and even that of SB-1024. In other words, the evenly spaced shells of GD more efficiently reduce or limit the number of broadcast

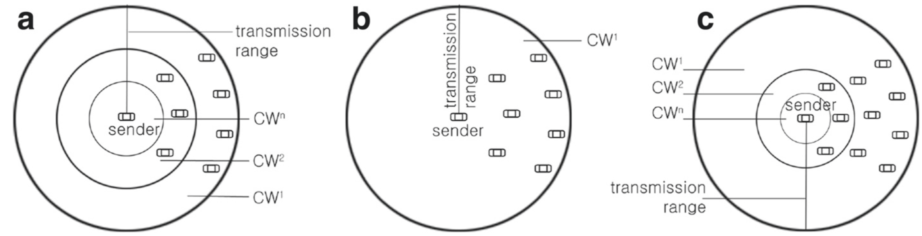

Fig. 3 Distribution of the CW size of the nodes in the sender's transmission range. **a** GD-based. **b** SB-based. **c** RSS-based

competitors, compared to the unevenly spaced shells of RSS.

From the two observations, we draw two conclusions. One is that the simple broadcast can be efficient in terms of propagation delay if it has a proper contention degree, as shown by SB-1024. The other comes from the implicit space limiting by GD and RSS. We hypothesize that a proper space limiting method that reduces the number of competitors for broadcasting helps to achieve a low propagation delay and a low collision rate simultaneously. From the hypothesis, we propose LAB, an explicit space limiting scheme for controlling the number of broadcast competitors in SB.

4 Limited area broadcast scheme

As mentioned in Section 2, an intelligent broadcast scheme can be considered as a broadcast relay selection scheme to restrain the broadcast storm. In this section we propose the limited area broadcast (LAB) scheme, which selects broadcast relay nodes by explicitly limiting an area in which only the nodes can compete with each other for broadcasting. Adjusting the size of the area enables the LAB scheme to control the degree of contention, which results in a short propagation time as well as a proper collision rate. Our scheme assumes all the nodes or cars are equipped with GPS for geographical information. The scheme is made up of two parts: relay node selection and broadcast procedure.

The basic concept of explicitly limiting the area in which a relay node can be selected is described in Fig. 4. If a broadcast sender designates an area, only the nodes in the area can resend the message. The first rebroadcasting node in the area becomes a relay node.

As depicted in Fig. 4b, a sender of LAB (either a source node or a relay node) located at $S(x_s, y_s)$ will send a broadcast message including $P(x, y)$ and r, which are the centers of the limited area and the radius of the limited area, respectively.

Because all the receivers that can overhear the message know their locations, $R(x_r, y_r)$s, they can immediately determine whether they exist in the area by using the simple equation, $\text{dist} = \sqrt[2]{(x_r - x)^2 + (y_r - y)^2}$. If $\text{dist} \leq r$, the node is allowed to compete for rebroadcast as one of the relay node candidates. If one of the candidates successfully rebroadcasts, the sender will overhear the messages as an acknowledgement of its broadcast message. If the sender cannot receive the rebroadcast message within a certain time[4], it means none of the nodes is selected as a relay node. In this case, radius r will be doubled as a sort of congestion control technique, similar to that of IEEE 802.11 contention window or that of TCP; the distance from $S(x_s, y_s)$ to $P(x, y)$ will be decrease as much as r increases. Then, the sender will send the unacknowledged broadcast message again. The radius r will be extended up to the maximum transmission range if the sender does not receive the same message continuously. The detailed procedure of LAB is described in Algorithm 2.

5 Simulation results and discussions

To evaluate our scheme, extensive simulations have been performed with traffic accident scenarios on a four-lane one-way road, as shown Fig. 1.

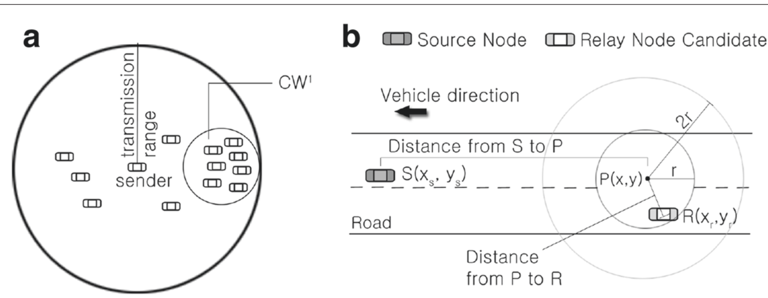

Fig. 4 LAB Scheme. **a** The distribution of the CW sizes of the nodes in the sender's transmission range. **b** Relay selection scheme

Algorithm 2 Broadcast procedure with LAB scheme

```
function RECEIVEBCASTMSG()
    msgID, S(x, y) → stored                         ▷ Store the message ID and sender position
    if packet(msgID) = sent then
        drop packet;
    end if
    PROCESSBCASTMSG(r);                             ▷ Call this function
end function
function PROCESSBCASTMSG(r)
    pos(r_x, r_y) ← R(x, y)                         ▷ Get the node position
    D = trange − r;                                 ▷ Set the value of Distance between Source to P(x,y)
    pos(p_x, p_y) ← S((x + D), y)                   ▷ Get the center position P
    distance = sqrt[2]((r_x − p_x)^2 + (r_y − p_y)^2)   ▷ Calculate the distance from P(x,y) to the receiving node
    if distance < r then                            ▷ Set as relay node
        BCASTMSG();                                 ▷ Call this function
        packet(msgID) ← sent
    else
        drop packet;
    end if
end function
function BCASTMSG()
    CW = CWsize                                     ▷ Set CW as 64
    S(x, y) ← R(x, y)                               ▷ Set location of receiver as sender
    rslot = random(CW);                             ▷ Set the slot
    if rslot = 0 then                               ▷ Count down the slot
        SENDBCAST();                                ▷ Call this procedure
    end if
end function
procedure LISTEN()
    while Sending do                                ▷ Listen to the backward message
        if Receive the message then                 ▷ Overhear the message
            RECEIVEBCASTMSG();                      ▷ Call this function
            received = true;
        end if
    end while
    if received = false then
        r = r * 2;                                  ▷ Update the value of radius r
        PROCESSBCASTMSG(r);                         ▷ Reprocess the message
    end if
end procedure
```

5.1 Simulation environment

We divided the road into three parts: (*i*) collision area, (*ii*) frozen area, and (*iii*) incoming car area. The frozen car area may have a low, medium, or high network density in this simulation. The low density area contains 25 cars/km/lane with an approximately 4-m gap between cars. The medium density area contains 50 cars/km/lane with an approximately 20-m gap between cars. The high density area contains 100 cars/km/lane with only an approximately 10-m gap between cars. The warning messages were randomly initiated by multiple broadcast senders (1, 2, 3, or 4) inside the collision area only once because we wanted to precisely measure the performance metrics by eliminating the adverse effect of mixed deliveries of the next broadcast and the current broadcast. Thus, the simulation time was 1 s to wait for all the broadcasts in the network to disappear. We repeated the 1-s simulation run 1000 times with different random seeds to obtain the averaged value.

In the simulation, we measured four performance metrics of SB, RSS, GD, and LAB as the number of broadcast senders and the network density were changed. The first metric was the single hop propagation delay because we found that the total propagation delay is not a good metric. Owing to the very low broadcast arrival rate of some broadcast schemes, the total propagation delay graph was distorted and brought incorrect results. The second is the number of collisions during the single hop propagation. From the second metric, we can understand why the single hop propagation delay increases or decreases. The third metric is the average number of hops used to deliver a warning message from the source to the last destination. From the first and the third metric, we can approximately estimate the total propagation delay. The last metric is the successful broadcast rate or reception rate, which can indicate the reliability of each broadcast scheme. It is defined as the ratio of the number of successful broadcast arrivals to the total number of broadcast initiations.[5] For the simulator, we have implemented our own simulator using the C language instead of using well-known simulators such as NS-2 and OMNET++ because we wanted to remove the side effects of other network components such as routing protocols. The detailed simulation configuration is summarized in Table 1.

Table 1 Simulation parameters

Simulation parameter	Value
Simulation time	1 s
Number of iterations	1000
Road length	5000 m
Road type	4-lane road
Vehicle density	25, 50, 100 cars/km/lane
MAC Protocol	IEEE 802.11p
Packet size	200 Byte
Data rate	2 Mbps
Slot time	10 us
Transmission range	250 m
Propagation model	two-ray ground
RXThreshold	8.91754e−10 mW (−90 dBm)
LAB-25 parameter	
CW size	64
Distance to P(x,y)	225 m
Radius of relay selection area	25 m
LAB-50 parameter	
CW size	64
Distance to P(x,y)	200 m
Radius of relay selection area	50 m
SB-64 parameter	
CW size	64
SB-1024 parameter	
CW size	1024
GD-based parameter	
CW size	32
Max. range	250 m
RSS-based parameter	
CW size	32
Min.rss (250 m)	8.91754e−10 mW
Max.rss (2 m)	4.80696e−5 mW

5.2 Simulation results

5.2.1 *Simple broadcasts with different CWs and different network densities*

The purpose of the first simulation was to investigate the relationship between CWs and network densities and their effects on single hop propagation delay and the number of collisions in the delay. Thus, we evaluated the performance of SBs with combinations of different CWs from 32 to 1024 and the three densities. In this simulation, a single broadcast sender was initiated in the collision area to eliminate the effect of multiple broadcast senders.

Figure 5 compares the propagation delays of each SB. As we expected, a longer propagation delay was introduced by a higher network density, which means the degree of contention becomes higher in the transmission range. At the same time, larger CWs caused shorter propagation delays because fewer collisions occur with larger CWs. In the worst example, the propagation delay of the CW of 32 drastically increases as the network density increases. As we increased the CW up to 1024, the rate of increase was reduced. The reason is based on how many collisions occur before the single hop broadcast succeeds at the given CW. In other words, if there are more collisions before a broadcast success, the single hop propagation delay becomes longer. To clarify the reason, we counted the number of collisions during the single hop propagation and drew Fig. 6 to show the average number of collisions. The cases of the CWs of 32, 64, 128, and 256 clearly follow the linearly increasing relation between the number of collisions and the delay. The cases of the CWs of 512 and 1024, however, show unexpected results in which the delay decreases as the density increases. The decline degree of the CW of 1024 is more definite than that of the CW of 512, which seems to be marginal. We believe the reason is as follows.

It is notable that the CWs of 512 and 1024 have almost zero collisions, as shown in Fig. 6, which means there is no collision before the broadcast success. Thus, the delay is not dependent on the number of collisions but on the size of the contention window of the first broadcast forwarder. For example, each broadcast node in SB with CW will randomly select a number between 0 and CW (= 512 or 1024) for its own CW and the smallest CW will be the CW of the first node to broadcast. As the network density increases,

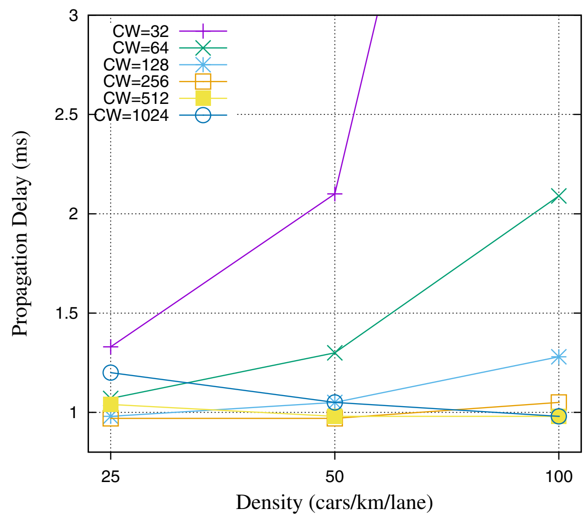

Fig. 5 Single hop propagation delays of simple broadcasts measured in low, medium, and high densities with different CWs

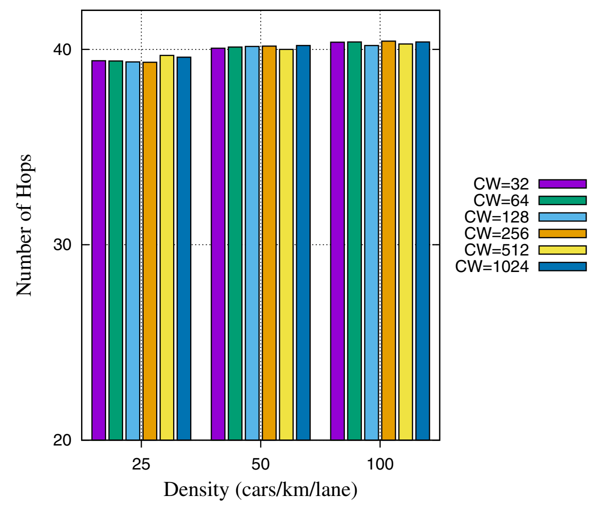

Fig. 7 Average numbers of hops of simple broadcasts needed to arrive at the destination in low, medium, and high densities with different CWs

the size of the smallest CW would decrease, which leads to a shorter propagation delay.

Figure 7 show the average number of hops needed to arrive at a destination. Because the number of hops depends on the average distance of a single hop and the total distance from the broadcast initiator to the destination, we can simply estimate the number of SBs by calculating $\frac{\text{(a whole distance)}}{\text{(a wireless transmission range/2)}}$ because the mean distance of a single hop of an SB will be half of the wireless transmission range. In our simulation, the number is 40 because the whole distance is 5000 m and the transmission range is 250 m. In Fig. 7, however, the numbers are not exactly but approximately 40. Moreover, the numbers are less than 40 at a density of 25 and increase slightly as the density increases.

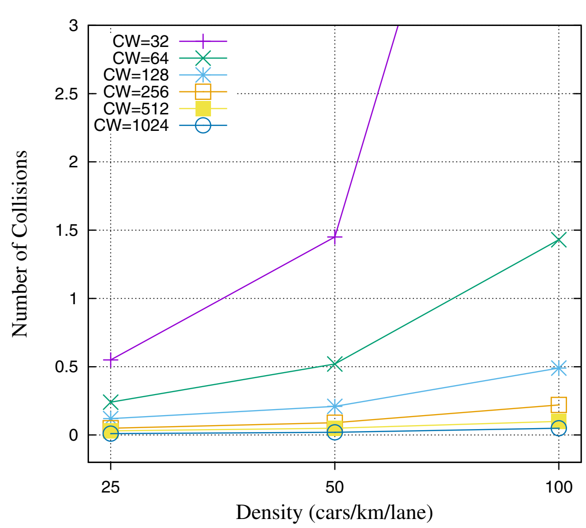

Fig. 6 Numbers of collisions of simple broadcasts counted in low, medium, and high densities with different CWs

The increasing pattern can be explained by a simple numerical analysis using the gap between cars depending on the density. For simplicity, the cars are assumed to be regularly located on a one-lane road instead of four-lane road. Then, for example, the gap distance in the low density area (= 25 cars/km/lane) will be 40m. Because the transmission range is 250 m, six cars can be covered from a sender. Thus, because the average number of cars covered in a broadcast is 3.5 cars, the average distance of a single broadcast transmission is 140 m (= 3.5 $\times$ 40 m), which is also the average distance of a single hop. From this distance, we can estimate the number of hops in the low density area as approximately 36 (= 5000 m/140 m). From the same calculations, the average numbers of hops in the medium and high densities will be 38.4 and 40, respectively. However, the measured numbers are larger than the calculations. Because this simulation assumes a four-lane road instead of a one-lane road, zig-zag forwarding paths from the sender to the destination are formed on the four-lane road. Thus, the number of hops on a four-lane road will be greater than that on a one-lane road.

Figure 8 shows the reception rate or the successful broadcast rate out of 1000 broadcast initiations. Only the CW of 32 achieves a low rate (= about 63 %) at a density of 100, which means the size of the CW is not sufficient to resolve the degree of contention at a density of 100.

5.2.2 Four scheme comparison with different network densities

In the second simulation, we compared the four schemes (SB, GD, RSS, and LAB) using four broadcast initiators

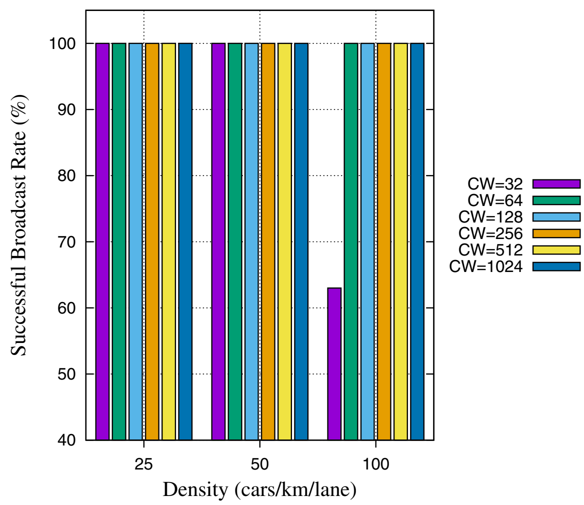

Fig. 8 Successful broadcast rates of simple broadcasts measured in low, medium, and high densities with different CWs

in the collision area. Four initiators in a higher network density tend to place more burdens on the network by increasing the number of flying broadcast messages, as well as the number of broadcast competitors or contentions. SB-64 and SB-1024 are simple broadcasts with CWs of 64 and 1024, respectively. GD and RSS are distance-based broadcasts. Depending on the distance from a sender, they adjust the CW from 32 to larger values. LAB-25 and LAB-50 limit the broadcast areas with radiuses of 25 and 50 m, respectively.

Figure 9 shows the single hop propagation delays of four broadcasts. With four broadcast initiators, RSS has the worst performance and SB-64 also drastically increases its delay as the network density increases. SB-64 seems to be natural because the degree of contention will increase as the number of initiators and the density increase, which results in an increase in collisions before the single hop broadcast success. The performance of RSS can also be understood as explained in Section 3. Because the CW of RSS is inverse-exponentially determined, the nodes in the outmost area will have its CW as 32 and experience many collisions, as shown in Fig. 10.

Figure 10 presents the number of collisions counted during the single hop broadcast propagation. From Figs. 9 and 10, we can understand the delays are dominated by the numbers of collisions. It is notable that we can verify the effectiveness of the spacing limitation by comparing LAB-25, LAB-50, and SB-64 because LAB-25, LAB-50, and SB-64 are the same in that they are based on SB using 64 for their CW. The only difference between them is that LAB explicitly limits the area in which broadcasts are allowed. The effect of explicitly limiting space to reduce the degree of contention of LAB-25 and LAB-50 seems impressive if we consider the numbers of collisions between SB and LAB. LAB-50 is worse than LAB-25 as the density increases. Because the area limited by LAB-50 is larger than LAB-25, the degree of contention will be higher in higher density and the collisions will be more frequent than LAB-25, which leads to a longer propagation delay than LAB-25. GD and LAB-25 seem to be comparable and similar in the number of collisions and the delay while SB-1024 achieves the best performance. Because the CW of 1024 is large enough to resolve contentions even in high density, the number of collisions becomes less than one, which results in the shortest delay. However, the shortest single hop delay does not mean the

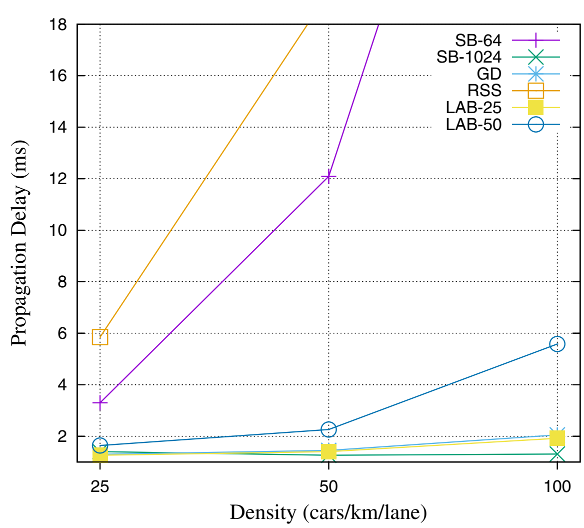

Fig. 9 Single hop propagation delays of four broadcasts measured in low, medium, and high densities with four broadcast initiators

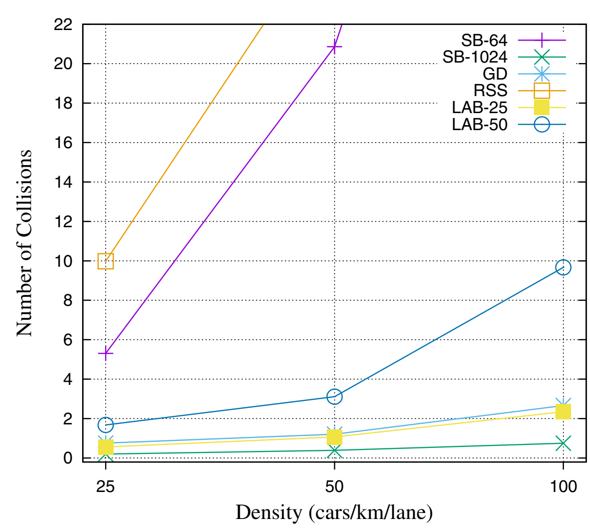

Fig. 10 Numbers of collisions of four broadcasts counted in low, medium, and high densities with four broadcast initiators

shortest end-to-end propagation delay from a sender to the destination. If we refer to Fig. 2 again, the performance in terms of the end-to-end propagation delays and collisions is in the order of GD, SB-1024, RSS, and SB-64. The order is strongly related to the number of hops of each scheme to the destination.

Figure 11 shows the average number of hops needed by the four broadcast schemes to arrive at the destination. SB-64 and SB-1024 achieve about 40 hops from a sender to the destination[6]. Because (the single hop delay) × (the number of hops) will be the end-to-end delay, as plotted in Fig. 2, SB-64 achieves the worst performance. Even though the number of hops of SB-1024 is 40, it is comparable to GD because its single hop delay is so short. From RSS, GD, and LAB in Fig. 11, moreover, we can understand how the average distance of a single hop against the total distance determines the average number of hops. The averages are mush lower than 40 because they achieve longer average transmission ranges depending on each SB scheme. For example, in the cases of GD and RSS, the probability that nodes in the outmost area will be selected is higher than those in the inner areas. Thus, we can approximate that the average distance of a single hop of GD or RSS will be the distance from the center (or a sender's location) to half of the thickness of the outmost shells. The average distance of a single hop of RSS is shorter than that of GD because the thickness of the outmost area of RSS is larger than that of GD. The shorter distance of RSS results in a higher number of hops compared to GD. The similar reasoning can be applied to LAB. In the case of LAB, the average distance of a single hop is the distance from a sender to the center of the limited broadcasting area because a broadcast forwarder will be randomly selected within the limited area with a radius r. As a result, the numbers of hops of RSS and GD should be approximately 25 (= 5000 m/200 m) and 22 (= 5000 m/225 m), respectively. However, the measured number of hops of LAB in the simulation is not exactly matched but very similar to the calculations. Except for LAB-50, the numbers of hops of RSS, GD, and LAB-25 increase slightly as the density increases. We guess the reason would be the same as that of the increasing pattern in the numbers of hops of SBs. In other words, the gap between cars will be smaller as the density increases; this results in a shorter distance for a single hop, as explained in the first simulation of SBs.

Figure 12 shows the rates of successful broadcasts that arrived at the destination out of 4000 broadcast initiations. Even though four broadcast initiators generate their own broadcast messages once during a single simulation run lasting for 1 s, the degree of contentions was serious: four times more than that of one broadcast initiator. SB-64 experiences a severe increase in broadcast propagation failures. At a density of 100, only about 12 % of the broadcasts successfully arrived at the destination. RSS also experienced severe broadcast message drops before the destination, although not as many as SB-64 did. These severe failures occurred because the CWs of SB-64 and RSS are not large enough to avoid a single hop broadcast failure. LAB-50 also experiences many failures at a density of 100, which implies that the limited area of LAB-50 could not sufficiently reduce the degree of contentions. Because SB-1024, GD, and LAB-25 provide a CW that is large enough to avoid single hop broadcast failures, they achieve broadcast reception rates of almost 100 %. If we remember that SB-64 and LAB-25 are the same in terms of

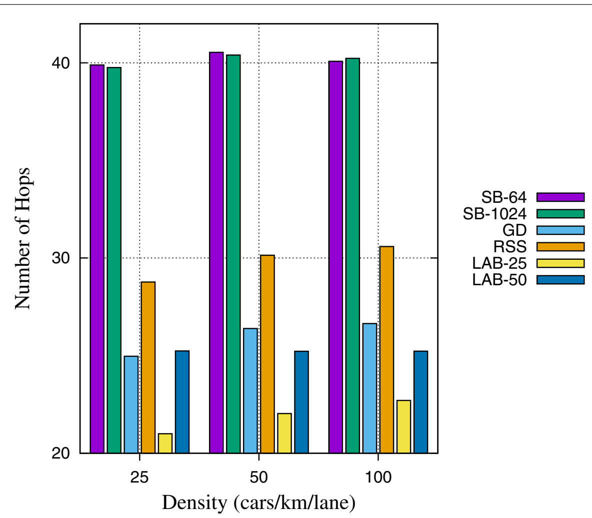

Fig. 11 Average numbers of hops of four broadcasts needed to arrive at the destination in low, medium, and high densities with four broadcast initiators

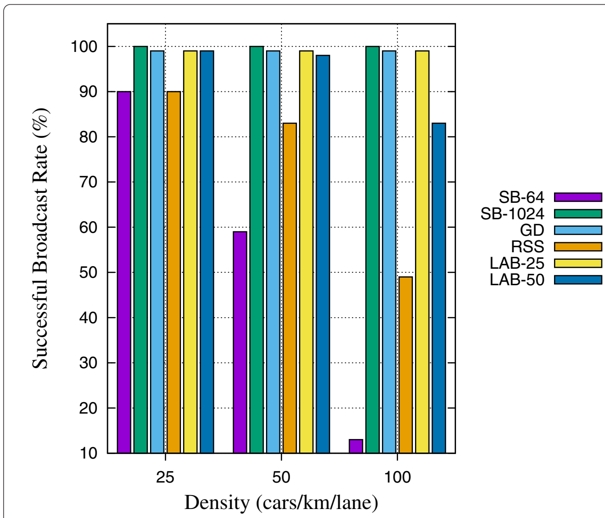

Fig. 12 Successful broadcast rates of four broadcasts measured in low, medium, and high densities with four broadcast initiators

CW size, we can see the effectiveness of properly limiting broadcast space to control the broadcast storm.

5.2.3 Four schemes comparison with different network densities and multiple senders

In this simulation, we fixed the network density at 50. For the four schemes (SB, GD, RSS, and LAB), we examined the effect of changing the number of broadcast senders from 1 to 4. Increasing the number of broadcast initiators provides more overhead to the network.

Figure 13 shows the single hop propagation delay of the four schemes as the number of broadcast senders is changed from 1 to 4. Because increasing the number of senders means increasing the number of flying broadcast messages, the degree of contentions will increase. As the degree of contentions increases, the number of collisions increases, as shown in Fig. 14. We can see that the single hop propagation delays in Fig. 13 follow the collision curves in Fig. 14. Because RSS and SB-64 do not have CWs that are large enough (32 and 64, respectively) to handle contentions when the number of senders is 3 or 4, the delays, including the time wasted by collisions, rapidly increase. LAB-50 and LAB-25 can gain the benefits of shorter delays from limiting broadcasting spaces because the number of contentions was reduced by limiting the broadcasting area for the CW (=64). Thus, we can also see the performance of SB-64 can be further improved by our suggestion. As we expected, LAB-25 is better than LAB-50 because the limited area of LAB-25 is smaller than that of LAB-50, which leads to a lower degree of contentions for a given CW (=64). LAB-25 and GD exhibit similar delays from similar numbers of collisions. SB-1024 is the best because the size of the CW is large enough for a given degree of contentions, and the fewest collisions occur.

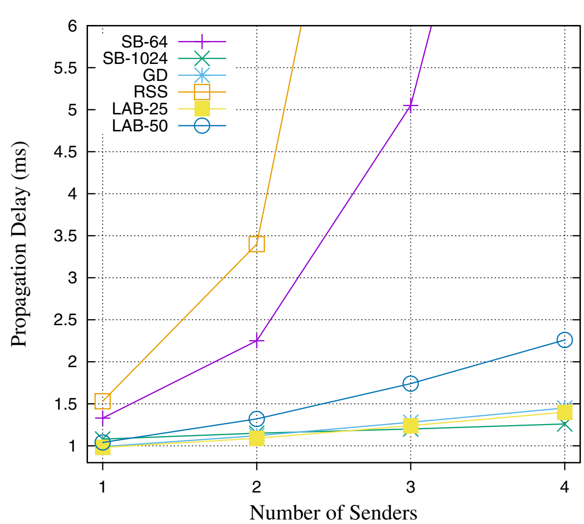

Fig. 13 Single hop propagation delays of four broadcasts measured in low, medium, and high densities with different broadcast senders

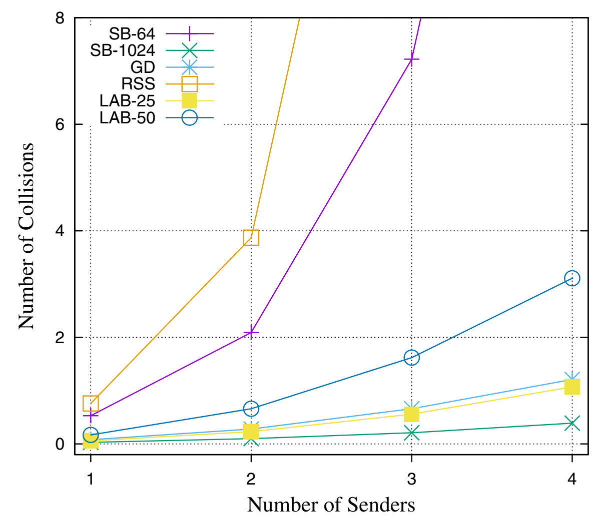

Fig. 14 Numbers of collisions of four broadcasts counted in low, medium, and high densities with different different broadcast senders

However, as explained in the second simulation, a shorter single hop propagation delay cannot give us a good end-to-end propagation delay because the end-to-end propagation delay is the product of the single hop delay and the average number of hops from a sender to a destination. Figure 15 shows the average number of hops of each broadcast as the number of senders changes. The numbers of hops in Fig. 15 seem to be constant even when the number of senders changes. If we compare Figs. 11 and 15, we can observe slight differences in the numbers of hops. We suppose the reason is as follows. At a fixed number of senders, increasing the network density affects

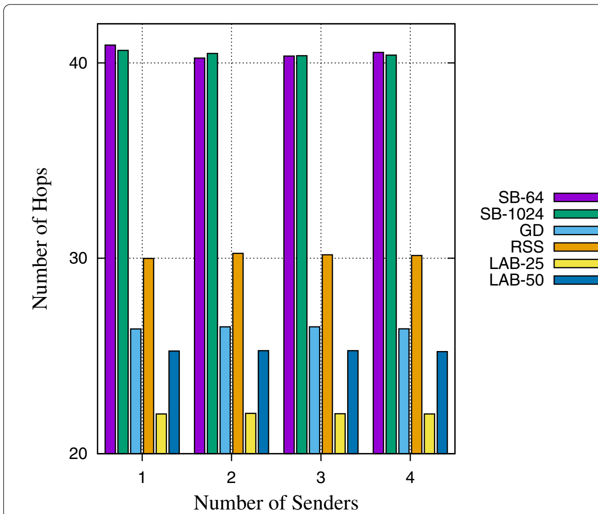

Fig. 15 Average numbers of hops of four broadcasts needed to arrive at the destination in low, medium, and high densities with different broadcast senders

the car locations on the road, which results in the change in the single hop distance. At a fixed network density, increasing the number of senders does not affect the car locations but affects the degree of collision; as a result, the average numbers of hops in Fig. 15 were measured to be constant.

Figure 16 shows the reception or arrival rates of each broadcast. Because SB-64 and RSS have more frequent collisions in a single hop propagation, they are more likely to have a broadcast failure in a single hop, which will be counted as a broadcast propagation failure. Actually, the reception rate for SB-64 and RSS drastically decreases as the number of senders increases. SB-64 is the worst and RSS performs second worst. If we consider the number of collisions in Fig. 14, RSS experiences more collisions than SB-64. The observation does not exactly match the assumption that more collisions would lead to lower reception rates.

The reason the reception rate of RSS is better than that of SB-64 can be explained as follows. The majority of RSS collisions occur in the outmost area because the size of the CWs of the nodes in the area is 32, which is not large enough to prevent collisions when the number of senders is 3 or 4. The nodes in the inner areas will have CWs that are larger than 64, enough to have a successful single hop transmission in the outmost area, while SB-64 has a fixed CW of 64, which is not large enough to handle the contentions when the number of senders is 3 or 4. Thus, RSS has a lower probability of having a single hop broadcast failure than SB-64, which results in the higher reception rates of RSS compared to SB-64. The remainder of the broadcasts do not experience significant decreases in the rate even when the number of senders changes. The slight decreases of the rates in LAB-25 and LAB-50 are found when the number of senders is 4.

5.2.4 *Additional comparison with different broadcast schemes with multiple senders*

In this simulation, we compared LAB to other broadcast schemes such as probability-based (PB), counter-based (CB), and density-based(DB) broadcast with four broadcast senders in the collision area. In the simulation, the size of the CW of each broadcast was 64. 0.5 was used for the transmission probability of PD. In other words, out of two packet transmissions on a single node, one packet may be transmitted while one packet may be dropped. Because the number of overhearing packets in CB was three, broadcasting a packet on a node will be cancelled only after overhearing three broadcast packets from neighbors. Otherwise, if the node cannot overhear three broadcasts from neighbors, it will perform its own broadcast. In DB, the transmission probability was adaptively changed to 0.4, 0.3, and 0.2 according to the low, medium, and high density of cars on the road, respectively.

Figure 17 shows the single hop propagation delays of four broadcast schemes. Because the contention degree significantly affects the delays, CB is the worst. As mentioned previously, a node in CB will cancel its broadcast only after the node overhears three broadcasts from neighbors. Otherwise, it will broadcast. Thus, the contention degree will be highest, which leads to the longest propagation delay. PB shows a relatively shorter delay than CB because the 0.5 transmission probability reduces the actual contention degree. However, as the network density increases, the delay also increases because the fixed probability cannot resolve the high contention degree at the higher network density. DB shows the semi-best performance because it can overcome the limits of PB by using

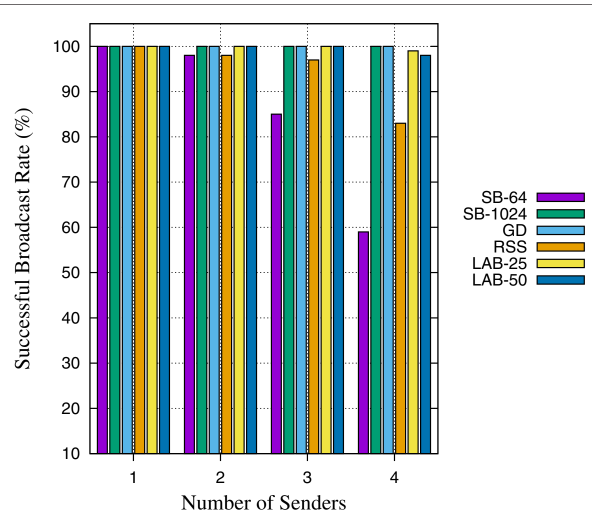

Fig. 16 Successful broadcast rates of four broadcasts measured in low, medium, and high densities with different broadcast senders

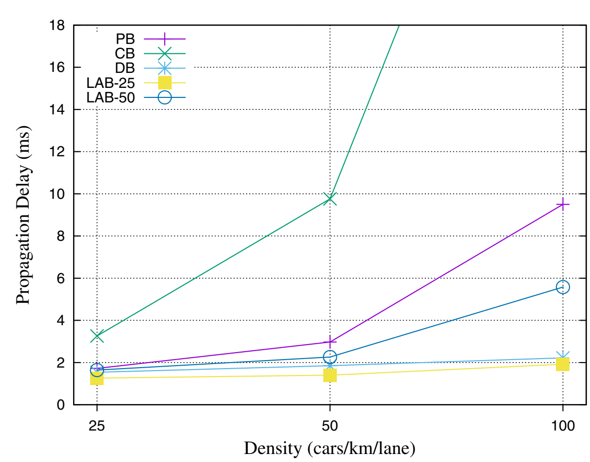

Fig. 17 Single hop propagation delays of four broadcasts measured in low, medium, and high densities with four broadcast senders

the adaptive transmission probability, depending on the network density. If the network density is higher, the probability becomes lower, which can control the degree of congestion competition. In the case of LAB, as mentioned previously, because the size of the limited space controls the degree of contention, LAB-25 shows better performance than LAB-50, even though the network density increases.

Figure 18 presents the number of collisions counted during the single hop broadcast propagation in Fig. 17. We easily determined that the order of performance in Fig. 18 is the same as that in Fig. 17, because the number of collisions until a single hop broadcast success is the major factor in the single hop propagation delay. It seems to be very clear that the number of collisions depends on the ability to control the contention degree. For example, because DB is using the adaptive packet transmission probability depending on the network density, it experiences a low number of collisions even at the high network density, while PB experiences a high number of collisions at the same network density. LAB-25 also efficiently controls the contention degree, and LAB-25 shows the fewest collisions.

Figure 19 shows the average number of hops needed by the four broadcast schemes to arrive at the destination. PB and DB achieve about 40 hops from the sender to the destination. This seems natural because PB and DB are very similar to SB except for their packet transmission probability. For example, SB can be considered as a PB with a packet transmission probability of 1.0. It is interesting that CB shows a lower number of hops than PB and DB while CB was the worst in terms of propagation delay. The CB's performance benefit can be explained with the following reasoning. In a single-hop transmission of CB, the three broadcasts were performed while only a single broadcast was performed in PB or DB. Thus, one of the three receivers of CB should always be located farther from the sender. The average distance from the sender to the receiver will be longer than those in PB and DB. LAB-25 and LAB-50 show the best and the second-best performance in the number of hops, as shown in Fig. 19.

Figure 20 shows the rates of successful broadcasts that arrived at the destination out of 4000 broadcast initiations, in the same manner as the previous simulations. PB and CB experience severe increases in broadcast propagation failures as the network density increases. At a density of 100, in the case of PB, only about 60 % of the broadcasts successfully arrived at the destination. More severely, in the case of CB, about 17 % of the broadcasts succeeded. These severe failures at the high network density result from a high degree of contention, which cannot be resolved. Because the packet transmission probability

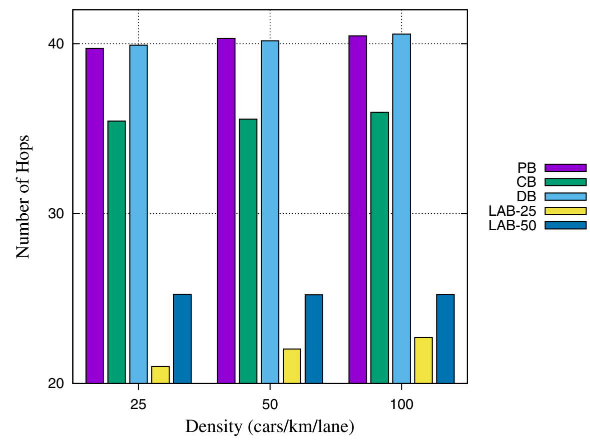

Fig. 19 Average numbers of hops of four broadcasts needed to arrive at the destination in low, medium, and high densities with four broadcast senders

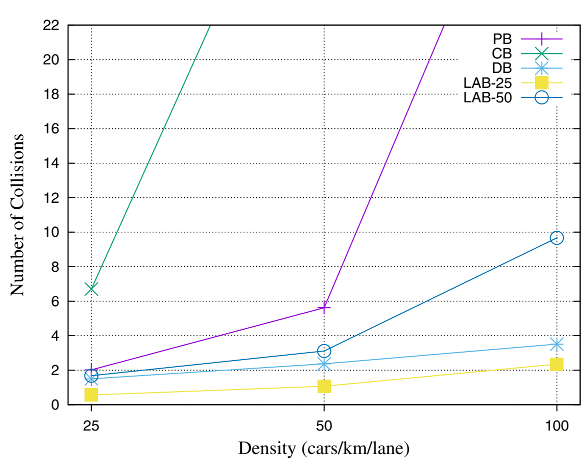

Fig. 18 Numbers of collisions of four broadcasts counted in low, medium, and high densities with four broadcast senders

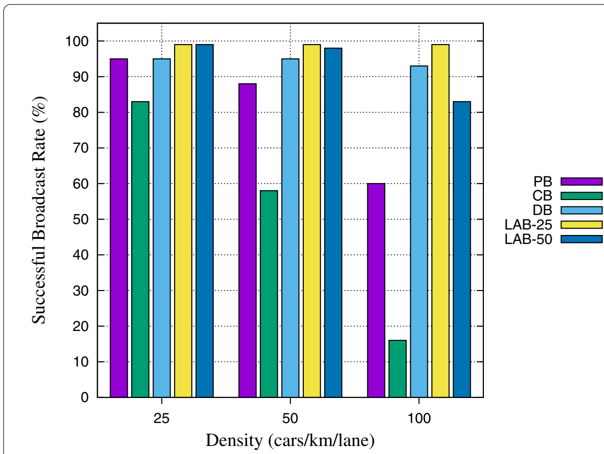

Fig. 20 Successful broadcast rates of four broadcasts measured in low, medium, and high densities with four broadcast senders

adopted by DB at the high network density can reduce the high degree of contention, DB's probability of single hop broadcast failure was low. The low probability results in a high successful broadcast rate, compared with PB and CB. LAB-50 also experiences many failures at a density of 100, which implies that the limited area of LAB-50 could not sufficiently reduce the degree of contentions. Because LAB-25 provides a degree of contention that is sufficient to avoid single hop broadcast failures, it achieves broadcast reception rates of almost 100 %.

6 Conclusions

In this work, we observed that even simple broadcast can be used to deliver emergency messages in a practical view[7] if it has a CW large enough to handle a high degree of contentions. In our simulation, SB with a CW of 1024, the largest size specified in the IEEE 802.11 standard, requires less than approximately 60 ms to travel 5 km with a reception rate close to 100 %. We know our simulation cannot cover all the cases and our results cannot be applied generally. However, we can see the possibility of SB's efficiency in the simulation.

We analyzed the reason why RSS is worse than GD in terms of the implicit spatial distribution of CWs, even though they are common distance-based broadcasts. From this observation, we developed the concept of explicit space limiting applied to SB to improve the broadcast propagation delay and proposed a new broadcast called LAB.

In one performance evaluation, we showed the simulation results of SB. Through the simulation, we analyzed the effects of the size of the CW and the degree of contentions on the propagation delays that result from the number of collisions. In addition, we could find the relation between the average distance of a single hop and the total traveled distance by determining the average numbers of hops.

Through simulations that compared four broadcasts with different network densities, we could verify the degree to which limiting the broadcast area with LAB could leverage SB to improve the propagation delay, the number of collisions, the average number of hops, and the reception rate. The simulation leads us to conclude that LAB with a proper radius seems to be robust to changes in network density and comparable to GD.

Through simulations that compared four broadcasts with multiple broadcast senders, we drew the same conclusion as that of the second simulations: that LAB is effective for controlling the broadcast storms.

Figure 21 summarizes the performances of four broadcasts by drawing the distributions of propagation delay and collisions[8]. In Fig. 2, each point of each scheme corresponds to one of the numbers of broadcast senders (1, 2, 3, and 4) and one of the network densities (low, medium,

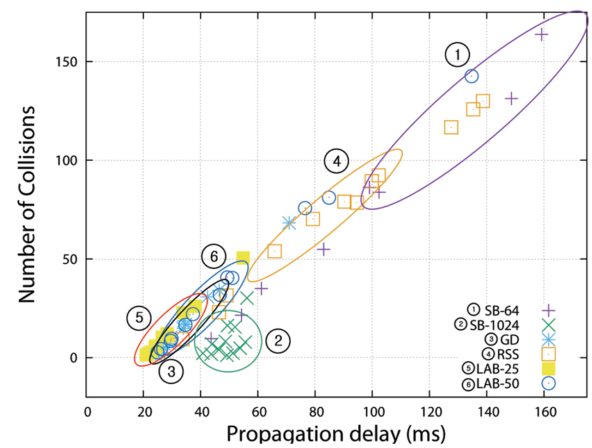

Fig. 21 Distribution of propagation delay and collisions of four broadcasts measured in low, medium, and high densities with different broadcast senders

and high). To clearly differentiate the distributions, we zoomed in on the scales of the x-axis and y-axis. We can see LABs are located very close to GD while the deviation of LAB-50 is bigger than those of LAB-25 and GD, which shows explicitly limiting a space to broadcast is effective for controlling broadcast storms on a dense network.

In this work, we did not discuss how to determine the initial radius of LAB based on the network density and the center location of a limited area. In the simulation, we used the predetermined values because we assumed a dense network on a four-lane road and a broadcasting situation after a car accident. As future work, in order to make LAB more complete, we plan to specify a method of determining the initial radius based on the network densities and the center location of the limited area. One possibility is to combine computer vision and the road's GPS information to obtain the density and the center location. In addition, we are going to consider applying LAB to an urban scenario with dynamic movement of vehicles as well as a dense network.

Endnotes

[1]Whenever a node overhears a broadcast message, it rebroadcasts the message again irrespective of how many times the nodes rebroadcasts the same message. We call this the pure broadcast scheme.

[2]We use the word "even" to indicate that the thickness of each shell is the same.

[3]CW^1 denotes the CWs in the outmost area. CW^2 denotes the CWs in the next inner area. CW^n also denotes the CWs in the consecutive inner areas.

[4]This time is estimated the same way as the RTT estimation used in TCP.

[5]In our simulation, the total number of broadcast initiations was 1000.

[6]We already discussed about why SBs have 40 hops in the first simulation.

[7]The message delivery can be completed in tens of milliseconds order which seems to be enough in terms of human sensitivity

[8]This propagation delay and the number of collisions are the total numbers from the broadcast initiation at a sender to the destination.

Competing interests
The authors declare that they have no competing interests.

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